FUEL REFORMING USING DIELECTRIC BARRIER DISCHARGE AND REFORMED FUEL EFFECTS ON BUNSEN FLAME

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Abstract

Methane and propane have been reformed using a dielectric barrier discharge (DBD) and the effect of the reformed fuel species on the combustion was investigated at a BUNSEN burner. The main output species of the DBD fuel reformer are composed of mixtures of hydrogen and other small hydrocarbons. DBD fuel reformer shows the characteristic of filamentary microdischarge. The conversion rate was less than 10% due to the low power loading of the DBD reactor. The reformed fuel species affect the BUNSEN burner flame significantly at high equivalence ratio and have an minor effect at stoichiometric and lean operating conditions. Experimental and numerical analyses are needed to investigate the effect of the reformed fuel on the combustion phenomena.

I. INTRODUCTION

Since German engineers invented internal combustion engine late 1800s, internal combustion engine has been the main power plant for transportation for well over 100 years. In the recent decades, the internal combustion engine has been faced with several challenging problems which make it uncertain that the existence of the internal combustion engine will serve as the main power plant for future transportation. Some examples of challenges are stringent regulations of exhaust emissions, market's demand for higher energy conversion efficiency, degraded fuel qualities, emerging alternative fuels such as biofuels, syngas, etc [1, 2]. New concept combustion technologies developed for the gasoline engine include ultra lean burn combustion, high exhaust gas recirculation (EGR), homogeneous charge compression ignition, etc that would attain higher thermal efficiency and low emission formation by reducing pumping and cooling loss. New concept combustion technologies for the gasoline engine, however, have not been mass-produced yet because of combustion instabilities and combustion phasing control issues at highly lean or exhaust gas diluted operating conditions [3]. Unstable combustion under lean or EGR diluted conditions is one of the main obstacles to overcome in the internal combustion engine and tremendous efforts have been centered to acquire the stable combustion at ultra lean and high EGR diluted condition. Recently new approaches have been proposed in order to attain stable combustion at severe engine operating conditions, which are modifying fuel properties by adding or mixing several different fuel species. In particular, hydrogen addition to the combustion system has shown a great impact on the combustion characteristics and exhaust gas formation of the conventional engine due to its unique properties. Hydrogen has unique characteristics in physical and chemical properties that are very different from those of typical hydrocarbon fuels. Hydrogen has a high laminar burning velocity and burning temperature, wide flammability limits, low Lewis number (ratio of thermal diffusion to species diffusion), low density and molecular weight, highest energy to weight ratio, etc. In particular, since hydrogen combustion does not generate carbon dioxide that is known causing global warming, hydrogen has become a potential alternative fuel for the future although hydrogen has many disadvantages to become a main transportation fuel owing to its low density (need four times the volume for a given amount of energy), explosive combustion speed, storage issues due to very low boiling point, etc. Due to the low density and explosive combustion speed, installing hydrogen storage tank into the conventional vehicle is not a practical solution and so, on-board hydrogen generation is promising option for hydrogen added enhanced combustion system for the transportation.

Many different fuel reforming techniques have been developed during last decades to generate hydrogen and other valuable hydrocarbons from natural gas and other fuels which may have applications in fuel cell, chemical process, pollution control, etc. [4, 5]. Typically three mechanisms have been used to reform hydrocarbons for generating hydrogen: steam reforming (SR), partial oxidation (POX), and autothermal reforming (ATR). Steam reforming is to combine steam with hydrocarbon fuels for producing hydrogen and simply can be expressed as shown in Equation 1.

$$C_xH_y + 2xH_2O = xCO_2 + (2x + y/2)H_2 \quad (1)$$

Since steam reforming can generate a high hydrogen concentration at a steady state and is a stable process, most of hydrogen produced in commercial scale is generated by steam reforming process. However, SR requires an enormous amount of energy to maintain the reactor temperature due to its intense endothermic

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14. ABSTRACT
Methane and propane have been reformed using a dielectric barrier discharge (DBD) and the effect of the reformed fuel species on the combustion was investigated at a BUNSEN burner. The main output species of the DBD fuel reformer are composed of mixtures of hydrogen and other small hydrocarbons. DBD fuel reformer shows the characteristic of filamentary microdischarge. The conversion rate was less than 10% due to the low power loading of the DBD reactor. The reformed fuel species affect the BUNSEN burner flame significantly at high equivalence ratio and have an minor effect at stoichiometric and lean operating conditions. Experimental and numerical analyses are needed to investigate the effect of the reformed fuel on the combustion phenomena.

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reaction. In addition to the required heat energy, SR process is slow and so, it is hard to start the reaction quickly. Therefore, SR is not appropriate for on-board fuel reformer for the internal combustion engine. Partial oxidation can be expressed as Equation 2.

$$C_xH_y + xO_2 = xCO_2 + y/2H_2 \quad (2)$$

Partial oxidation produces hydrogen by oxidizing the hydrocarbon fuel with less amount of oxygen than that of stoichiometric condition. Incomplete combustion of hydrocarbon generates the mixture of hydrogen, carbon monoxide, and carbon dioxide. Due to the exothermic characteristics of POX, the process has quick response time. However, the hydrogen selectivity is lower than that of SR and high operating temperature for the reaction requires special reaction chamber and has low overall energy efficiency due to joule heating and energy loss of the reactor. Autothermal reforming is a combined technology of SR and POX and can be expressed in Equation 3.

$$C_xH_y + xH_2O + x/2O_2 = xCO_2 + (x + y/2)H_2 \quad (3)$$

Since the ATR utilizes the advantages of SR and POX simultaneously, the heat balance can be changed by the degree of exothermic and endothermic reactions. The ATR doesn't require the external heat source and also can maintain the reaction at lower temperature than that of POX. Thus, it is possible to make ATR with small scale and relatively high efficiency. However, due to the complexity of the reaction in ATR, it requires a sophisticated control of operating conditions for the optimal combination of POX and SR reactions.

This study presents experimental results of fuel reforming using a dielectric barrier discharge (DBD) and its effects on BUNSEN burner flame.

II. EXPERIMENTAL SETUP AND RESULT

A. *Experimental Setup*

Figure 1 shows the experimental setup for a DBD fuel reformer and BUNSEN burner. BUNSEN burner shown in Figure 1 has been built to investigate laminar premixed flame in which premixed mixtures of air and reformed fuel are inducted through four inlet manifolds and fully mixed before entering the flame zone. The detail of the DBD fuel reactor is drawn in Figure 2 and has a simple geometry. Alumina plates (1mm thickness) are placed between the electrodes and high voltage AC power is supplied via function generator and high voltage transformer. AC voltage and frequency are regulated by the function generator. The gap between the dielectric plates has been set to 3mm and the electrode has 1.5 inch by 3.5 inch. Therefore, the active area for DBD reaction is 33.87 cm^2. The reformer box is made of acrylic plate (0.5 inch) and cooled by circulating the tap water. The reformed fuel was speciated using a gas chromatography that has TCD (Thermal Conductivity Detector). TCD detector (Agilent micro GC3000) which has four measuring channels and two carrier gases (helium and argon) measures relative population of hydrogen, CO, CO_2, N_2 and low hydrocarbons (C_1 and C_2

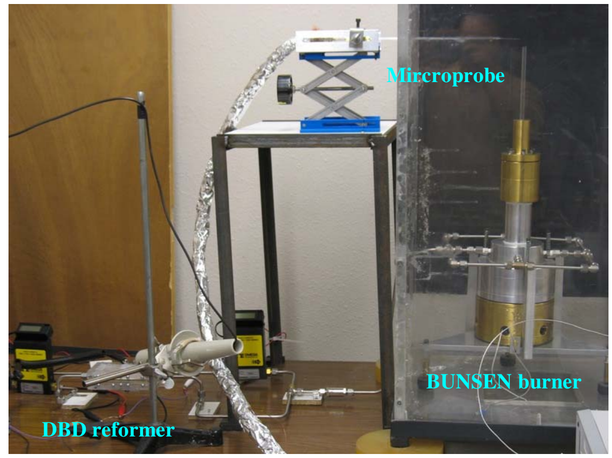


Figure 1. Experimental setup for DBD fuel reformer

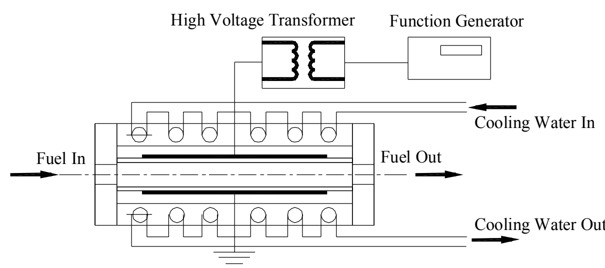
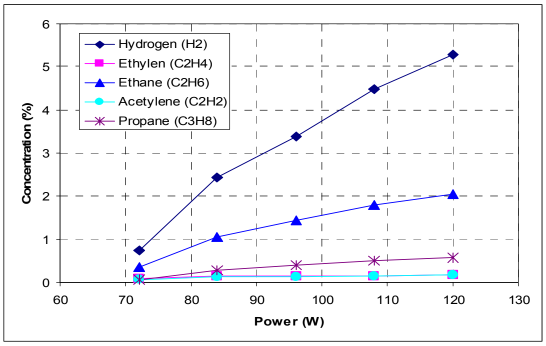


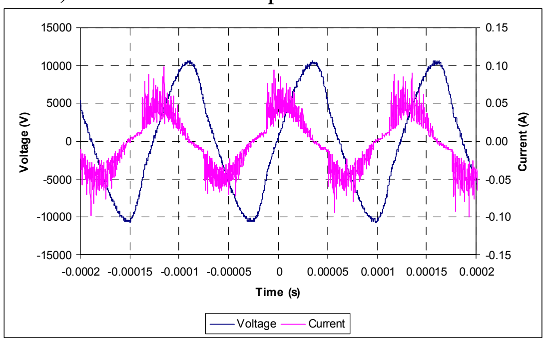
Figure2. Schematic configuration for DBD reactor

B. *Test Condition and Result*

Fuel reforming test has been conducted with pure methane and propane gases. The flow rate of methane and propane has been fixed to 0.3 l/min and the air flows are controlled to change the equivalence ratio. Figure 3 presents the measured reformed fuel species and electrical characteristic of the methane reforming. Power input has been varied from 72 Watt to 120 Watt. Fuel conversion rate defined as the converted fuel species ratio to the input fuel is less than 10%. Hydrogen and ethane are dominant reformed fuel species and the small amount of hydrocarbons including ethylene, acetylene, propane, etc have been detected. Second graph in Figure 3 represents the electrical characteristics of methane DBD reaction. Sinusoidal voltages were applied to the reformer and the measured current shows the typical filamentary type micro discharge with nano second time scale.

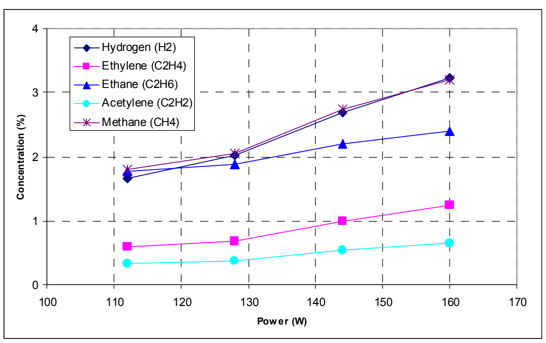


a) Reformed fuel species of methane

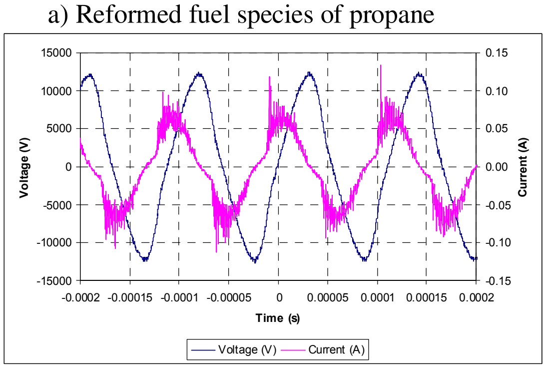


b) Electrical characteristics of methane discharge

Figure3 Reformed fuel species from methane conversion



a) Reformed fuel species of propane



b) Electrical characteristics of methane discharge

Figure 4 Reformed fuel species from propane conversion

Figure 4 shows the measured fuel species and electrical properties for the propane gas reforming. The main reformed fuel species are hydrogen, methane, and ethane. Measured electrical characteristic is almost same with that of methane and the breakdown down voltage is a little higher than that of methane.

Figures 5 shows BUNSEN burner flame structure at different equivalence ratio using the reformed methane fuel. At each equivalence ratio, the fuel flow rate was fixed and the amount of air was changed to control the fuel/air ratio. In Figure 5, the upper picture shows the flame structure and the lower pictures taken by thermal camera represents the thermal distribution of the flame. Equivalence ratio (Φ) 1 represents the stoichiometric air fuel ratio, equivalence ratio greater than 1 means rich and less than 1 is lean. Left flame at each equivalence ratio represents the base flame using pure methane and the right indicates reformed fueled flame. It is well known that the premixed laminar BUNSEN burner flame shows the double flame structure.

Φ=1.2 Φ=1.0 Φ=0.95

Base Reformed fuel

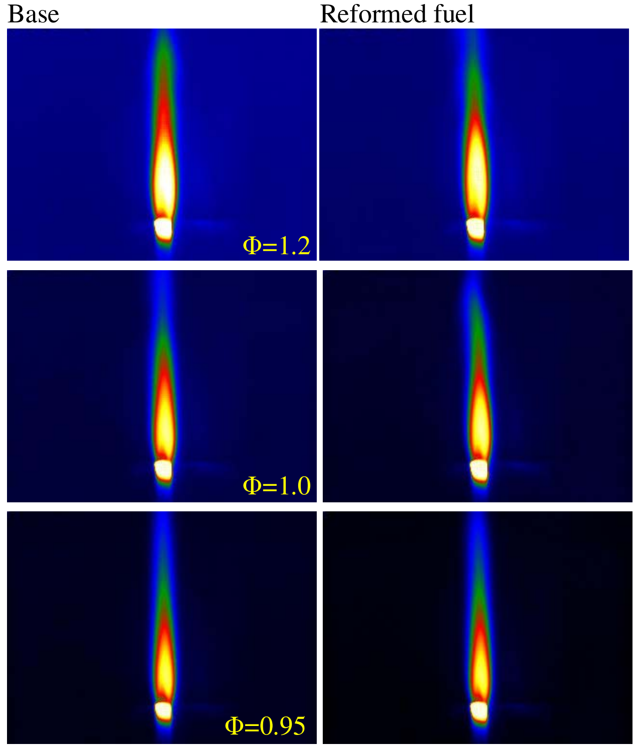
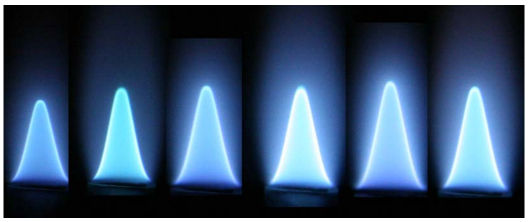


Figure 5 BUNSEN burner flame of methane

At the inner flame zone, chain reactions (initiation, propagation, and termination) are occurring and eventually hydrogen and carbon monoxide are generated. Hydrogen and carbon monoxide are combusted with

oxygen at the outer area and generate water vapor and carbon dioxide. As shown in Figure 5, the reformed fuel makes the flame longer at rich air fuel ratio and at stoichiometric and lean condition BUNSEN flame of reformed fuel is almost same with that of base fuel. The corresponding thermal image indicates that the reformed fuel species make the inner flame longer, which means the hydrogen enriched fuel has affect combustion chain reaction at the inner flame. That is, H radicals have an important impact on combustion chain reaction process and the detailed mechanism of the effect of hydrogen addition to BUNSEN flame should be more investigated.



Φ= 1.1　　Φ=1.0　　Φ= 0.95

Base　　Reformed fuel

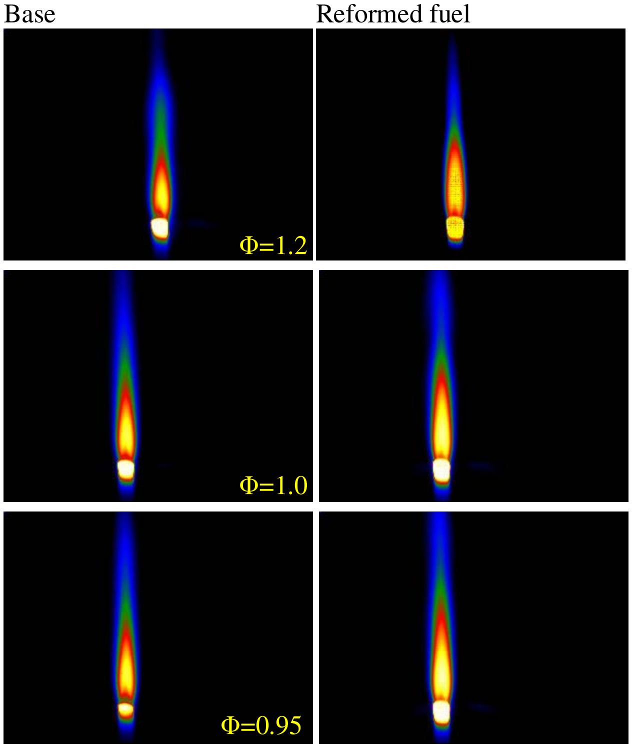


Figure 6. BUNSEN burner flame of propane

Figure 6 represents the propane flame pictures and the overall effect of the reformed fuel is same with that of the reformed methane species. The effect of the reformed propane was more influential at high equivalence ratio.

III. SUMMARY

The present paper presents initial experimental results of the fuel reforming using a dielectric barrier discharge and shows the effect of the reformed fuel on BUNSEN burner flame at different equivalence ratio. The reformed fuel species of methane and propane are mainly composed of hydrogen, ethane and other small hydrocarbons. Since the power density of the DBD reactor was low, the fuel conversion efficiency of the DBD reactor showed less than 10%. The reformed fuel species have more affected on the BUNSEN burner flame at high equivalence ratio. The detailed experimental and numerical analyses are needed to understand the added H radicals on the flame chain reactions.

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